A Differentiated Optical Services Model for WDM Networks *

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Abstract

This article addresses the issues of scalable end-to-end QoS in Metropolitan DWDM networks serving as transit networks for IP access networks. DWDM offering few wavelengths have in the past been deployed in backbone networks to upgrade point-to-point transmission where sharing is based on coarse granularity. This type of DWDM backbone networks offering few lightpaths, provides no support for QoS services traversing the network. As DWDM networks with larger numbers of wavelengths penetrate the data-centric Metro environment, specific IP service requirements such as priority restoration, scalability, dynamic provisioning of capacity and routes, and support for coarse-grain QoS capabilities will have to be addressed in the optical domain in order to achieve end-to-end QoS over a DWDM network. We propose a QoS service model in the optical domain called Differentiated Optical Services (DoS) based on a set of optical parameters that captures the quality and reliability of the optical lightpath.

1 Introduction

It is becoming increasingly evident that Dense Wavelength Division Multiplexing (DWDM), offering multi-gigabit rates per wavelength, will soon become the core technology for the next generation Internet. However, harnessing the unprecedented bandwidth offered by DWDM to meet the rapidly growing Internet traffic in the metropolitan network environment will require DWDM networks to be optimized for IP services and IP QoS . Optical networks such as SONET/SDH have been traditionally perceived as high-capacity transmission pipes with negligible delays and transmission errors. As a consequence, it is generally argued that the effort to develop an effective QoS for optical networks cannot be justified, since individual packets or even aggregated flows cannot be tracked and controlled optically,

*A preliminary version of this article was presented during SPIE 1999 Conference on All Optical Networking Architecture [1] especially at gigabit rates. However, DWDM networks are now emerging that offer multiple alternate lightpaths with different optical quality between a single source-destination [2]. This makes it possible to classify each alternate optical route according to its quality of optical transmission, reliability, and other selected optional capabilities.

The proliferation of QoS on the Internet coupled with the fact that Internet traffic will eventually be aggregated and carried over DWDM networks are the motivating factors for addressing the issues of optical quality of service. As IP becomes increasingly the dominant protocol of choice for data transmission, there is a growing need to devise QoS models in order to handle applications that require strict performance requirements beyond the traditional IP best-effort service. An IP QoS model that has been extensively studied in the literature is the Integrated Services (Int-Serv) [3]. It is based on the definition of several traffic classes that, if supported by the network routers and switches traversed by IP flows, can deliver packets to their destination with certain QoS commitments. Int-Serv requires a signaling mechanism, such as the ReSerVation Protocol (RSVP) [4], to reserve network resources along the flow path. With Int-Serv, each packet in the network is processed by the router to determine its service class. In large IP networks, the processing and policing of individual packets impose a computation burden on the packet forwarding engine that limits the scalability of Int-Serv. The Differentiated Services (Diff-Serv) model [5] was introduced to deal with the scalability issue in the Int-Serv service model. In Diff-Serv, scalability is achieved by aggregating packets with the same QoS requirements into fewer but coarser-grain flows. This significantly reduces the computational burden since the packet forwarding engine has to police fewer coarse-grain flows. Diff-Serv flows are enforced locally on a per-hop basis, further simplifying the complexity of end-to-end QoS policing mechanisms.

A further aggregation of Diff-Serv flows into coarser-grain flows can be directly mapped into optical channels at rates of OC-12, OC-48, and OC-192. The mapping may be performed in such a way that the optical quality of the lightpath matches that of the aggregate Diff-Serv flows. The main objective of this paper is to propose a model for optical QoS for DWDM networks that maps well with the Diff-Serv model. The remainder of the paper is structured as follows. In section 2, we review a framework for optical differentiated services based on the ITU-T G.872 reference architecture [6]. Our Differentiated Optical Services (DoS) model is described in section 3 and issues pertaining to its implementation discussed in section 4. Concluding remarks are offered in section 5.

2 Differentiated Optical Services Framework

In this section we discuss a framework for implementing Differentiated Optical Services (DoS) in DWDM networks. The DoS model that we propose in the next section largely depends on this framework, so an understanding of it is essential to the description of the model. Emerging optical networks built with DWDM can be classified into two broad categories: 1) Wavelength Division Multiple Access (WDMA) optical networks which are primarily variations of *broadcast-and-select* LANs realized with single or multiple hops DWDM links, and 2) DWDM-based Optical Transport Networks (OTN) for long-haul and metropolitan environments. WDMA networks are still experimental and we shall therefore focus exclusively on the emerging OTN described in ITU-T Recommendation G.872 [6]. A layered architecture for OTN is shown in Figure 1. It comprises functional capabilities provided by optical network elements for transport, multiplexing, routing, supervision, and survivability of client signals that are processed predominantly in the optical domain. The optical network elements considered include optical Regenerator (1R, 2R, 3R), Optical Amplifier (OA), optical wavelength multiplexer/demultiplexer, Optical Add/Drop Multiplexer (OADM), and Optical Crossconnect (OXC).

The generic functional capabilities of OTN can be decomposed into three independent logical transport layers:

1. The Optical Transmission Section (OTS) - provides the functionality for transmission of optical signals on various types of optical media. Functions provided by OAs reside in this layer.

2. The Optical Multiplex Section (OMS) - provides the transport of a multi-wavelength optical signal including the insertion of the multiplex section overhead to ensure the integrity of the signal. It also provides multiplex section survivability. Optical network elements that belong to this layer are Wavelength multiplexers and fibre crossconnects.

3. The Optical Channel (OCh) section -provides end-to-end networking of optical lightpaths for transparently carrying various client signals (e.g. SDH, ATM Cells, and IP packets). It also prepares and inserts an overhead for the channel configuration information such as wavelength tag, port connectivity, payload label (rate, format, line code), and wavelength protection capabilities. This layer contains OXCs and OADMs functionality.

An optical lightpath defined in this context is an optical communication channel, traversing one or more optical links, between a source-destination pair. In a typical mesh DWDM network, there can be several lightpaths between a single source-destination pair, each with unique optical characteristics. Therefore a lightpath is uniquely identified by a set of optical parameters (BER, delay, jitter) and behaviors (protection, monitoring and security capabilities) that provide the basis for measuring the quality of optical service provided on the path. This measure is in turn used to divide lightpaths into groups that define classes of optical services equivalent to IP QoS classes. The optical lightpath concept constitutes a major building block for our Qos Model.

Another key element that we highlight in this framework is the QoS-Aware layer that we add to the G.872 architecture as shown in Figure 1. This layer where electro-optical conversion takes place, contains most of our QoS model functionality and provides a mapping of Diff-Serv services onto equivalent optical services. The QoS-Aware layer is closely coupled to the OTN network management that is required to provide support for fault, configuration and performance management end-to-end.

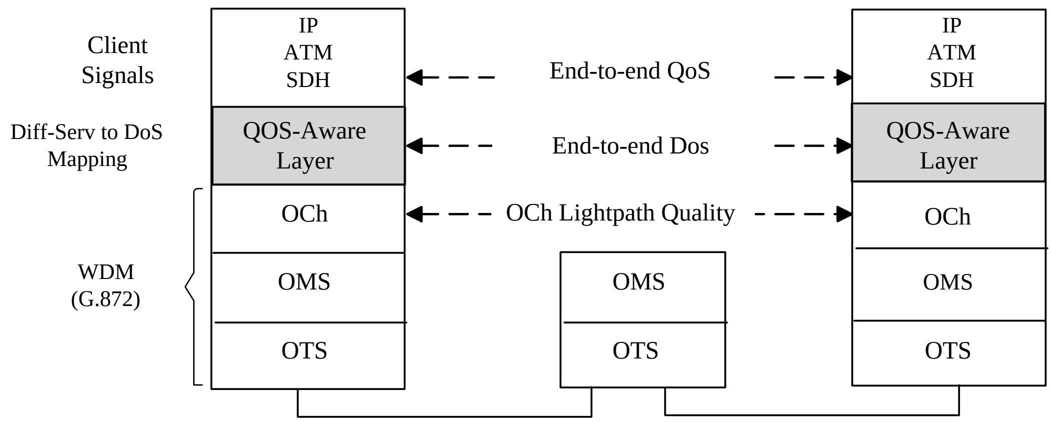

Figure 1: Optical Transport Network Architecture

3 Differentiated Optical Services Model

In this section, we describe the concept of optical quality of service [2] akin to Diff-Serv, suitable for the DWDM framework discussed in section 2. A major design issue for a DWDM QoS model is scalability due the coarse-grain aggregation nature of DWDM especially at gigabit data rates (e.g. OC-48 and OC-192). This implies that a heavy computational burden must be overcome if the DWDM edge device has to process, track, and maintain the QoS state of each flow of the aggregated traffic in the optical domain. Thus the QoS model that we propose consists of applying a Diff-Serv approach to the DWDM environment. The similarities of our model with Diff-Serv constitutes a significant advantage that could be exploited to develop efficient support of IP differentiated services in DWDM networks. The DoS model that we propose consists of the following four components:

- an architectural model that defines the boundaries of a DoS domain including interface modules that classify and condition ingress traffic.
- service classes defined by a set of parameters and functional capabilities.
- mapping of traffic flows and service classification performed at the edge of the network.
- signaling and optical resource allocation performed in the optical domain.

3.1 DoS Architectural Model

An architectural model which defines the differentiated optical services domain and captures the concept of end-to-end QoS in a global network environment is depicted in Figure 2. It consists of two access networks A_1 and A_2 interconnected by a backbone network. The access networks are IP networks supporting Diff-Serv (implemented on ATM/SONET) while the DWDM transit network supports DoS. The DoS domain is defined as a set of core optical nodes such as OAs, OXCs, wavelength multiplexers and edge nodes consisting of OADMs where electro-optical conversion and traffic grooming takes place. DoS services are only defined at the edge nodes since DoS parameters are not visible in the core all-optical network. End-to-end services are provided by concatenating multiple domains (or clouds) that could be engineered or administered separately. This framework allows for flexibility in how each domain is implemented. The DoS domain consists of the following two major components:

1. The Interface Module- implements QoS-Aware functions for aggregating and mapping Diff-Serv flows originating from the access network onto equivalent optical flows with QoS parameters enforced in the optical domain. The performance characteristics of optical lightpaths at the OADMs are made available in this module in electrical form. Incoming Diff-Serv flows with similar requirements are aggregated to form a flow with a capacity equal to the standard commercially available optical capacity such as OC-12, OC-48, and OC-192.

2. The Optical Network - is an interconnection of multi-wavelengths capable optical components (OXCs, OADMs, OAs) in which the transmitted information along the lightpath, remains entirely in the optical domain. Conceptually, an optical network can be partitioned into two topologies:

   - The Physical Topology - that is a graphical representation of the interconnection of physical devices such as OAs, optical regenerators, wavelength multiplexer/demultiplexer terminals, OADMs (fixed and reconfigurable), wavelength and fibre OXCs (fixed and reconfigurable).
   - The Logical Topology - that is an induced graph on the physical network describing a logical routed network overlay, wherein logical switching nodes interconnect a set of unidirectional lightpaths that are atomic routeable objects that can be provisioned to carry aggregated flows with a defined QoS at OC-12, OC-48 and OC-192 rates.

3.2 DoS Parameters and Functional Capabilities

A DoS service is defined by a set of parameters that characterize the quality and impairments of the optical signal carried over a lightpath. These parameters are either specified in quantitative terms such

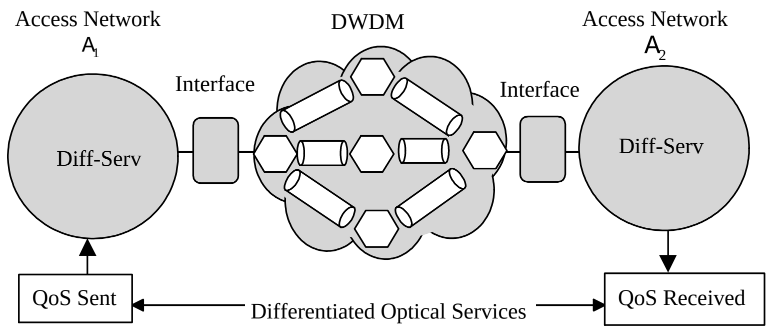

Figure 2: Differentiated Optical Services Domain

as delay, average BER, jitter, and bandwidth, or based on functional capabilities such as monitoring, protection and security [7]. Some of the relevant parameters that can be used to characterize the quality of the optical services are the following:

1. **Lightpath Characteristics** - The performance of a lightpath in DWDM is determined by the quality of the optical components along its path. Typically, as a transmitted signal carried over a lightpath traverses optical components such as optical crossconnects, fiber segments, and erbium-doped fiber amplifiers (EDFAs), it encounters undesirable impairments such as jitter, wander, crosstalk, and amplified spontaneous emission (ASE). These impairments tend to accumulate and can significantly degrade the quality of the transmitted signal as it progresses towards its destination. Most of these impairments translate into signal Bit Error Rate (BER) computed at the receiving node. Thus, BER is an important parameter for measuring the performance of a lightpath. Recently, a lightpath setup scheme based on an on-line BER estimation mechanism of candidate lightpaths was proposed [8]. In this scheme, each lightpath request is accompanied by a BER minimum threshold . The call is accepted if a lightpath is found that meets the specified BER threshold. The call is blocked otherwise. This simple admission policy can be generalized to include a multi-threshold scheme, each threshold designating a class of optical service with a specific quality of service. Other parameters for measuring the performance of a lightpath include jitter, power, gain, and ASE level.

2. **Lightpath Protection -** Since service availability is becoming increasingly a requirement for certain mission critical applications in the Internet, it is therefore important to make it also part of the optical QoS service model. The main objective is to render the lightpath transparent to failures such as fiber cuts and wavelength failures. Traditional SONET/SDH survivability mechanisms offer equal protection to all flows in the network. In a large-scale mesh optical network, such an approach to survivability is not cost-effective nor justifiable since the need

for guaranteed service availability in a Diff-Serv environment depends on the application. Thus a network survivability model that suits Diff-Serv traffic is one that implements class-based protection mechanisms. That is, Diff-Serv flows that require a specific degree of protection belong to a certain class of optical quality of service. In addition, the restoration time can be used to refine the different classes of protection. As previously stated, protection mechanisms in mesh DWDM networks realized with $(1:1)$ and $(1+1)$ do not scale as well as $(1:n)$ schemes [9]. However if $(1:n)$ schemes are used, any single fiber cut can be restored. This means that in the event of multiple failures in a network supporting a $(1:n)$ scheme, the network management needs to restore high priority lightpaths first. This is accomplished by differentiating and tagging lightpaths according to a priority scheme that reflects unique classes of quality of optical service. We can further extend the concept of $(1:1)$, $(1+1)$, and $(1:n)$ used for fiber protection to wavelength protection. That is, in addition to protecting the fiber, wavelengths are also protected.

3. **Lightpath Monitoring -** The ability to monitor trails for validity, integrity, and quality is a major part in the OTN control and management functionality. A number of methods have been considered to provide monitoring features. Some are available continuously while others can made available on demand on a per connection basis. This implies that a DWDM network could implement connection monitoring capabilities only on a selected subset of lightpaths, thus offering the monitoring capability only to a selected class of optical services. The three types of connection supervision being considered for standardization by the ITU-T relevant to our current problem include the following:

   (a) **Intrusive Monitoring** - the purpose of this type of monitoring is to test wavelength and fiber performance for continuity. It is achieved by breaking in the original trail and introducing a test trail that extends the connection for the duration of the test.

   (b) **Inherent Monitoring** - the client layer (IP, ATM, STM) continuously monitors the state of a given connection by processing the overhead provided by the OCh optical section layer to approximate the operational state of the client connection. Similarly, the OCh section layer processes the data received from the OMS layer to approximate the operational state of each OCh channel. The overall status of the connection cannot be achieved with this type of monitoring since not all the necessary information for performance monitoring is contained in the overhead information.

   (c) **Non-Intrusive Monitoring** - the connection monitoring capability is provided by listening to the original data and its associated overhead. The overhead information transported by a connection is also used for fault detection.

4. **Lightpath Security**- There is a need to provide transport of secure applications over public transport networks and optical networks in particular. Lightwave communications carrying multi-gigabits per second are vulnerable to various forms of service denials or eavesdropping attacks. Attacks on DWDM networks can be classified in three broad categories [10]:

   (a) Traffic Analysis and Eavesdropping- in which the attacker analyze the traffic and attempts to degrade its quality.

   (b) Service Denial - where the optical signal is disrupted by the attackers.

   (c) QoS degradation - the attacker overpowers legitimate optical signals with attack signals and may exploit crosstalk sensitive optical devices. This can be used to degrade or deny services.

   Thus, we envision in the near future, an increase in the demand of secure lightpaths. The methods to detect and prevent these types of attacks are still in their infancy.

5. **Lightpath Transparency**- The degree of lightpath transparency depends on the type of signal regeneration. A 3R regeneration (with retiming and reshaping) reclocks the signal however it completely eliminates transparency to bit rates and frame formats. 2R regeneration without retiming offers some transparency but leads to jitter accumulation at each regeneration step. 1R regeneration is the simplest form of regeneration where the signal received is retransmitted without retiming or reshaping.

3.3 Optical Service Classification and Mapping

The main goal of DoS is to provide a mechanism for offering a spectrum of services in the optical domain through a classification of lightpaths according to the end-to-end quality of optical transmission as shown in Figure 3. The optical services are accessed through an interface located at the ingress point in the optical networks usually at the WADMs where end points of the OCh trails are accessible. We identify the following functions to be implemented at the interface:

- Aggregation of incoming Diff-Serv flows into fewer flows at rates corresponding to lightpath traffic carrying capacity such as OC-48 and OC-192.

- Grouping of lightpaths (OCh Trails) into classes that reflect unique qualities of optical transmission

- Mapping of aggregated incoming Diff-Serv flows onto lightpath classes that correspond to the QoS of the aggregated flows.

- An aggregated flow admission control and policing function to ensure that OTN does not accept more Diff-Serv flows than the available optical resources in OTN can support.

Once Diff-Serv flows are mapped onto optical flows in OTN, the optical QoS parameters are enforced in the optical domain using the monitoring and signaling functionalities of the optical network management.

The set of lightpath characteristics and functional capabilities outlined in the previous section provides a basis for classifying the lightpaths and is negotiated in the QoS-Aware interface layer during call setup. An example of a three-class optical service differentiation requirements using the above criteria is shown in Table 1. It consists of three alternate lightpaths between a single source-destination

Classification Criteria	Class 1 (λ_1, λ_2)	Class 2 (λ_3, λ_4)	Class 3 (λ_5, λ_6)
BER	10^{-9}	10^{-7}	10^{-5}
Survivability	90%	70%	20%
Monitoring	Intrusive	Intrusive	Non-intrusive
Security	Secure	Unsecure	Unsecure
Provisioning	1R	2R	3R

Table 1: An Example of Optical Services Classification in OTN

pair accessible at the WADM, each with a unique DoS class, labeled class 1, class 2, and class 3, containing wavelength groups (λ_1, λ_2), (λ_3, λ_4), and (λ_5, λ_6), respectively as shown in Figure 3. All lightpaths in a DoS class have equivalent quality of optical service between a source-destination pair.

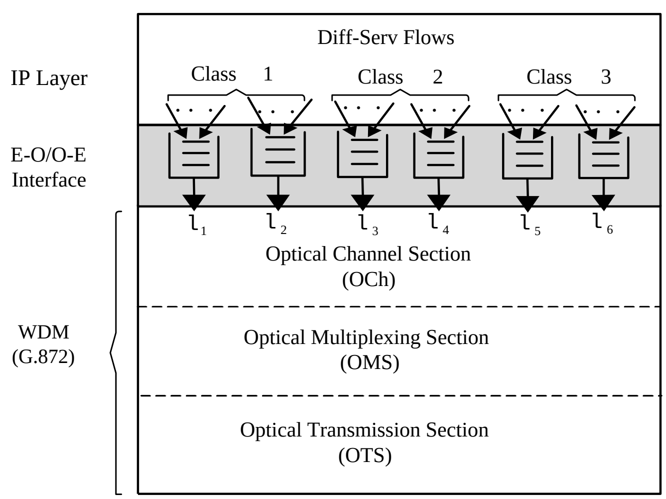

Figure 3: IP Differentiated Services Mapping

3.4 Signaling and Resource Allocation

In addition to policing and classification, reserving the optical resources is an equally important control function that is critical to making appropriate admission control decisions and to configuring the edge classifiers. Similar to the *bandwidth broker* abstraction in Differentiated Services, we define the concept of an **Optical Resource Allocator** specified over an optical domain that handles the dynamic provisioning of lightpaths. The Optical Resource Allocator keeps track of the resources such as the number of wavelengths, links, crossconnects, and amplifiers available for each lightpath and evaluates the lightpath characteristics (BER computation) and functional capabilities (protection, monitoring, security). The Optical Resource Allocator is also responsible for initiating end-to-end call setup along the chain of optical resource allocators representing the different domains traversed by the lightpath. It is part of the optical network management contained in the OCh section of the G.872 architecture and its implementation requires a signaling protocol to collect state information and reserve optical resources. This exchange of information among optical nodes is carried in the form of signal overhead that is generally used at all layers of the OTN for the purpose of trail identification, protection, alarm indication, configuration commands and performance monitoring. Techniques to transport overheads are generally classified into two broad categories: inband schemes and supervisory channels. Supervisory channels are extra channels allocated to carry the overhead associated with either a single or multiple OTN layers, inside or outside the amplification window. On the other hand inband schemes are generally related to each channel and include several techniques such as pilot tone, subcarrier modulation and framing/wrapping [11]. While pilot tones uses a different frequency for each channel, subcarrier modulation transports overhead data over subcarriers that have an identical frequency value for all channels. The wrapping technique depends on the client bit rate and consists of adapting the client frames into new frames to include the overhead. Recently ITU-T has adopted a digital wrapper technique for carrying OTN overhead information.

4 Implementation Issues

In this section, we address some implementation issues associated with the DoS model presented in section 3. We report on the state of the art in optical network management and performance monitoring since the implementation of DoS is heavily dependent on supervising the quality of optical lightpath and managing it end-to-end.

4.1 Optical Network Management

So far, management in WDM networks has been confined to point to point links. It is generally conducted with the help of a client equipment or developed separately for stand-alone solutions for each Network Element (NE). However with the advent of new optical NEs such as dynamically reconfigurable OADMs and OXCs, a dynamic system-wide management solution is needed. Furthermore, the DoS model presented in this paper puts additional constraints on optical network management. It requires that optical channels be supervised, provisioned, and signaled end-to-end.

Recently, several field experiments have been reported and management system prototypes built within the ACTS project. The common approach is to adapt generic Telecommunication Management Network (TMN) concepts to the WDM network architecture model and develop Management Information Models according to the principles defined in ITU-T M.3100. A solution outlined in [12], includes the definition of standard interfaces between the Equipment Management Layer (EML) and the Network Management Layer (NML). The main goal for this hierarchical approach is to hide equipment specific details and provide management at both the network and element levels.

Standardization bodies are about to start work on the definition of management concepts and information models for OTN. Until now the focus was on ITU-T Recommendation G.872 which provides an overview on the function architecture of OTN and some requirements for optical network management. Two new recommendations are planned: G.onm will include fault, configuration and performance management and G.oni will specify the information model for OTN network elements.

4.2 Performance Monitoring

At present, there are no simple optical performance monitoring techniques without regeneration available that can be installed in large numbers to assess the performance of the digital payload. The implementation of parameters that measure the quality of the optical service such as BER computation and signal degradation, requires some degree of electronic processing that is only present at the edge of the backbone network. Therefore the optical QoS parameters are only visible at the WADMs where electro-optical conversion of the signal is performed. The signal at the source point of the lightpath has some known quality and the degradation of this quality can be determined based on measurements at the sink or the edge of the optical nework. Performance thresholds are set up that trigger mandatory alarms operated by the management system and indicate the severity of the degradation of the signal. In addition, a number of restrictions can also be imposed on the configuration of the optical lightpath. Due to noise accumulation, nonlinearities and other physical effects, only a limited number of optical amplifiers and crossconnects can be cascaded in order to comply with the performance figures imposed by the service class requirements. This number is dependent on the client signal (bit rate, bit error rate) and the characteristics of the network element (such as their noise figures). Cascading rules can be defined based on the physical parameters of the equipments and some worst case assumptions. Cascading rules along with a set of mandatory alarms need to be standardized. At the same time more studies are required in order to determine the effects that influence the optical signal quality and that enable detecting degradation and identification of possible causes for it in the optical domain. Advanced techniques for optical channel monitoring, coherent cross-talk monitoring, bit-error probability estimation and optical signal-to-noise ratio measurement need to be refined and expanded. The possibility to estimate bit error probability from the optical signal alone without the need for bit by bit detection could constitute a powerful tool for recognizing slow signal degradations long before the client application.

5 Conclusion

Much effort has been spent in recent years on WDM network management and standards are currently being defined. However, a lot remains to be understood on how to characterize the quality of the optical lightpath and how to measure it according to standard performance criteria. In this paper we motivate the need for and formulate a quality of optical service model for WDM networks. We show how such a model provides the basic continuity needed to support end-to-end Diff-Serv flows traversing a transit WDM network. We also identify and analyze a set of optical parameters together with functional capabilities that provide a basis for lightpath differentiation. In order for DoS to be successfully deployed and commercially viable in the near future, a consensus on optical QoS needs to be achieved today and brought forward for standardization.

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